HERMETIC PACKAGES AND FEEDTHROUGHS FOR NEURAL PROSTHESES

Quarterly Progress Report # 10

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SUMMARY

During the past quarter, we continued testing the wireless humidity monitoring system and monitored the hermeticity of these packages in animal hosts. We continued to monitor, test, and develop the integrated humidity monitoring system; develop alternative methods for biocompatible packaging; and test the FINESS chip and finish the testing of the transmitter for transmitting adequate power to the FINESS chip.

Four glass-silicon packages have been soaking on PBS at room temperatures. As of the end of this quarter, all these packages are still intact and the longest package has been soaking for a total of 2139 days. These packages will continue their soak test until failure is detected.

A wireless system that consists of a hybrid coil and a polyimide relative humidity sensor has been developed. We have packaged a wireless system and soaked in high temperature saline and after 18 months in saline at 97°C, the humidity monitoring system is functional and the package is still dry (confirmed with visual inspection). Six glass-silicon packages with HMS systems have been implanted into various locations in two guinea pigs and after 17 months they all indicate that the packages are hermetic and intact. Additional nine packages with wireless humidity sensors are soaked in saline at 95°C, 93°C, and 85°C. After 83 days 3 packages have failed due to unknown causes while the remaining 6 show little or no sign of polysilicon etching.

A fully-integrated humidity sensor with on-chip coil and capacitor has also been designed and is in fabrication. This humidity sensor simplifies package testing and will be used for testing. An accurate model for the FI-HMS system continues to be developed. New test structures and devices have been fabricated to obtain more data from which a better model can be derived.

Significant advances have been made in biopackaging. We have demonstrated the use of electroplated gold films as a hermetic seal for neural probe circuitry. Furthermore, we have begun work on biocompatible flip chip design by investigating solder bonding for interconnections. We have demonstrated improved solder bonding by using our experiences in eutectic bonds.

In the past quarter, we tested the FINESS chip. As a first step, we directly powered the chips and probed the stimulation outputs. We plan to continue testing in the current quarter, and move on to remote powering with a Class E transmitter.

6I. INTRODUCTION

This project aims at the development of hermetic, biocompatible micropackages and feedthroughs for use in a variety of implantable neural prostheses for sensory and motor handicapped individuals. In addition, it will also develop a telemetry system for monitoring package humidity in unrestrained animals, and of telemetry electronics and packaging for stimulation of peripheral nerves. The primary objectives of the proposed research are: 1) the development and characterization of hermetic packages for miniature, silicon-based, implantable neural prostheses designed to interface with the nervous system for many decades; 2) the development of techniques for providing multiple sealed feedthroughs for the hermetic package; 3) the development of custom-designed packages and systems used in several different chronic stimulation or recording applications in the central or peripheral nervous systems in collaboration and cooperation with groups actively involved in developing such systems; and 4) establishing the functionality and biocompatibility of these custom-designed packages in *in-vivo* applications. Although the proposed research is focused on the development of the package and feedthroughs, it also aims at the development of inductively powered systems that can be used in many implantable recording and stimulation devices in general, and of multichannel microstimulators for functional neuromuscular stimulation, and multichannel recording microprobes for CNS applications in particular.

Our group here at the Center for Integrated Sensors and Circuits at the University of Michigan has been involved in the development of silicon-based multichannel recording and stimulating microprobes for use in the central and peripheral nervous systems. More specifically, during the past three contract periods dealing with the development of a single-channel inductively powered microstimulator, our research and development program has made considerable progress in a number of areas related to the above goals. A hermetic packaging technique based on electrostatic bonding of a custom-made glass capsule and a supporting silicon substrate has been developed and has been shown to be hermetic for a period of at least a few decades in salt water environments. This technique allows the transfer of multiple interconnect leads between electronic circuitry and hybrid components located in the sealed interior of the capsule and electrodes located outside of the capsule. The glass capsule can be fabricated using a variety of materials and can be made to have arbitrary dimensions as small as 1.8mm in diameter. A multiple sealed feedthrough technology has been developed that allows the transfer of electrical signals through polysilicon conductor lines located on a silicon support substrate. Many feedthroughs can be fabricated in a small area. The packaging and feedthrough techniques utilize biocompatible materials and can be integrated with micromachined structures.

The general requirements of the hermetic packages and feedthroughs to be developed under this project are summarized in Table 1. Under this project we will concentrate our efforts to satisfy these requirements and to achieve the goals outlined above. There are a variety of neural prostheses used in different applications, each having different requirements for the package, the feedthroughs, and the particular system application. The overall goal of the program is to develop a miniature hermetic package that can seal a variety of electronic components such as capacitors and coils, and integrated circuits and sensors (in particular electrodes) used in neural prostheses. Although the applications are different, it is possible to identify a number of common requirements in all of these applications in addition to those requirements listed in Table 1. The packaging and feedthrough technology should be capable of:

1- protecting non-planar electronic components such as capacitors and coils, which typically have large dimensions of about a few millimeters, without damaging them;
2- protecting circuit chips that are either integrated monolithically or attached in a hybrid fashion with the substrate that supports the sensors used in the implant;
3 interfacing with structures that contain either thin-film silicon microelectrodes or conventional microelectrodes that are attached to the structure;

Table 1: General Requirements for Miniature Hermetic Packages and Feedthroughs for Neural Prostheses Applications.

Package Lifetime:
≥ 40 Years in Biological Environments @ 37°C

Packaging Temperature:
≤360°C

Package Volume:
10-100 cubic millimeters

Package Material:
Biocompatible
Transparent to Light
Transparent to RF Signals

Package Technology:
Batch Manufactureable

Package Testability:
Capable of Remote Monitoring
In-Situ Sensors (Humidity & Others)

Feedthroughs:
At Least 12 with ≤125μm Pitch
Compatible with Integrated or Hybrid Microelectrodes
Sealed Against Leakage

Testing Protocols:
In-Vitro Under Accelerated Conditions
In-Vivo in Chronic Recording/Stimulation Applications

We have identified two general categories of packages that need to be developed for implantable neural prostheses. The first deals with those systems that contain large components like capacitors, coils, and perhaps hybrid integrated circuit chips. The second deals with those systems that contain only integrated circuit chips that are either integrated in the substrate or are attached in a hybrid fashion to the system.

Figure 1 shows our general proposed approach for the package required in the first category. This figure shows top and cross-sectional views of our proposed approach here. The package is a glass capsule that is electrostatically sealed to a support silicon substrate. Inside the glass capsule are housed all of the necessary components for the system. The electronic circuitry needed for any analog or digital circuit functions is either fabricated on a separate circuit chip that is hybrid mounted on the silicon substrate and electrically connected to the silicon substrate, or integrated monolithically in the support silicon substrate itself. The attachment of the hybrid IC chip to the silicon substrate can be performed using a number of different technologies such as simple wire bonding between pads located on each substrate, or using more sophisticated techniques such as flip-chip solder reflow or tab bonding. The larger capacitor or microcoil components are mounted on either the substrate or the IC chip using appropriate epoxies or solders. This completes the assembly of the electronic components of the system and it should be possible to test the system electronically at this point before the package is completed. After testing, the system is packaged by placing the glass capsule over the entire system and bonding it to the silicon substrate using an electrostatic sealing process. The cavity inside the glass package is now hermetically sealed against the outside environment. Feedthroughs to the outside world are provided using the grid-feedthrough technique discussed in previous reports. These feedthroughs transfer the electrical signals between the electronics inside the package and various elements outside of the package. If the package has to interface with conventional microelectrodes, these microelectrodes can be attached to bonding pads located outside of the package; the bond junctions will have to be protected from the external environment using various polymeric encapsulants. If the package has to interface with on-chip electrodes, it can do so by integrating the electrode on the silicon support substrate. Interconnection is simply achieved using on-chip polysilicon conductors that make the feedthroughs themselves. If the package has to interface with remotely located recording or stimulating electrodes that are attached to the package using a silicon ribbon cable, it can do so by integrating the cable and the electrodes again with the silicon support substrate that houses the package and the electronic components within it.

Figure 2 shows our proposed approach to package development for the second category of applications. In these applications, there are no large components such as capacitors and coils. The only component that needs to be hermetically protected is the electronic circuitry. This circuitry is either monolithically fabricated in the silicon substrate that supports the electrodes (similar to the active multichannel probes being developed by the Michigan group), or is hybrid attached to the silicon substrate that supports the electrodes (like the passive probes being developed by the Michigan group). In both of these cases the package is again another glass capsule that is electrostatically sealed to the silicon substrate. Notice that in this case, the glass package need not be a high profile capsule, but rather it need only have a cavity that is deep enough to allow for the silicon chip to reside within it. Note that although the silicon IC chip is originally 500μm thick, it can be thinned down to about 100μm, or can be recessed in a cavity created in the silicon substrate itself. In either case, the recess in the glass is less than 100μm deep (as opposed to several millimeters for the glass capsule). Such a glass package can be easily fabricated in a batch process from a larger glass wafer.

The above two approaches address the needs for most implantable neural prostheses. Note that both of these techniques utilize a silicon substrate as the supporting base, and are not directly applicable to structures that use other materials such as ceramics or metals. Although this may seem a limitation at first, we believe that the use of silicon is, in fact, an advantage because it is biocompatible and many emerging systems use silicon as a support substrate.

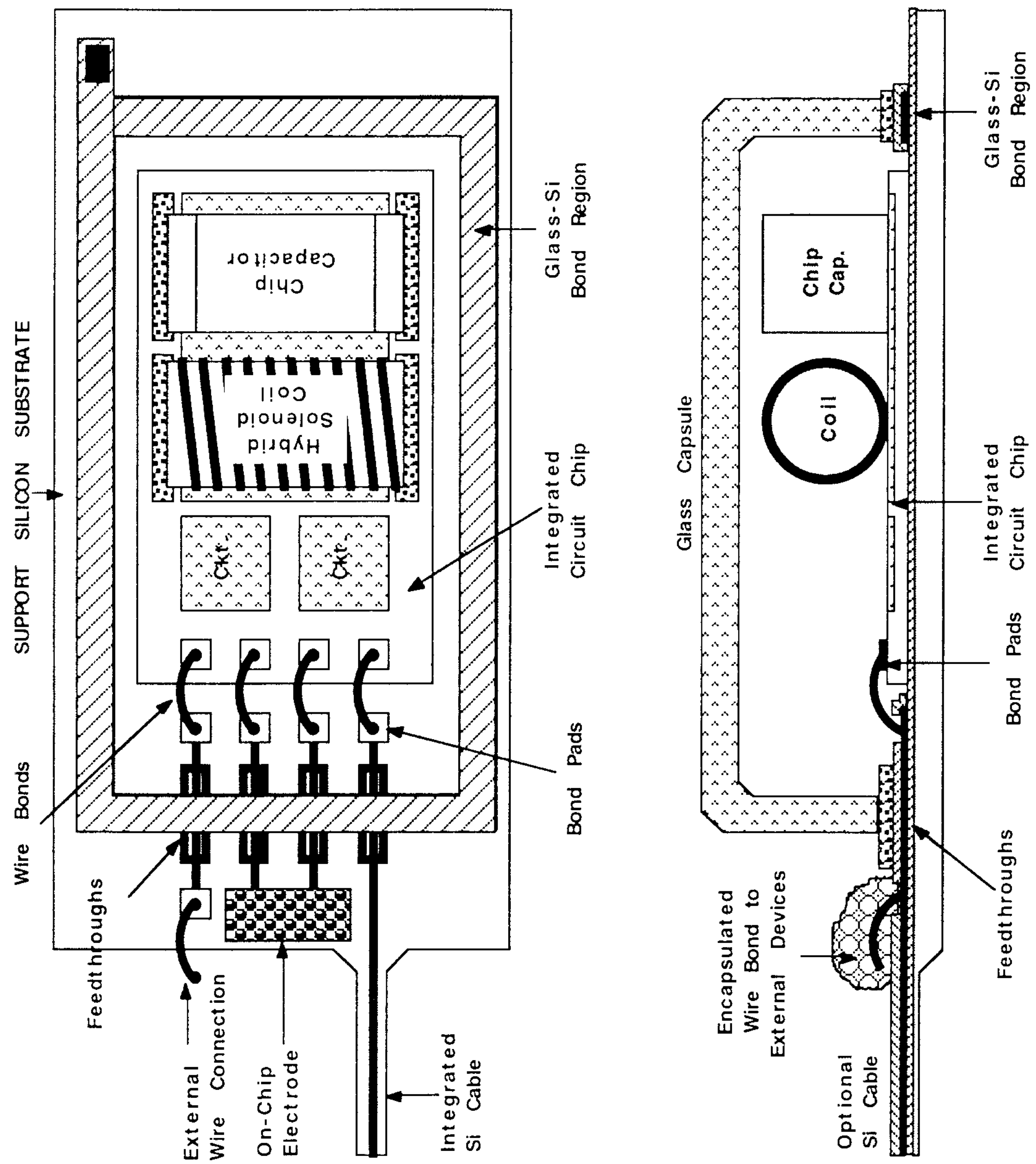


Figure 1: A generic approach for packaging implantable neural prostheses that contain a variety of components such as chip capacitors, microcoils, and integrated circuit chips. This packaging approach allows for connecting to a variety of electrodes.

We will further improve the silicon glass package and its built-in feedthroughs, and will study and explore alternative technologies for hermetic packaging of implantable systems. In particular, we have proposed using a silicon capsule that can be electrostatically bonded to a silicon substrate thus allowing the capsule to be machined down to dimensions below a 100μm. We will also develop an implantable telemetry system for monitoring package humidity in unrestrained animals for a period of at least one year. Two separate systems have been proposed, one based on a simple oscillator, and the other based on a switched-capacitor readout interface circuit and an on-chip low-power AD converter, both using a polyimide-based humidity sensor. This second system will telemeter the humidity information to an outside receiver using a 300MHz on-chip transmitter.

Finally, we have forged potential collaborations with two groups working in the development of recording/stimulating systems for neural prostheses. The first group is that led by Professor Ken Wise at the University of Michigan, which has been involved in the development of miniature, silicon-based multichannel recording and stimulation system for the CNS for many years. Through this collaboration we intend to develop hermetic packages and feedthroughs for a 3-D recording/stimulation system that is under development at Michigan. We will also develop the telemetry front end necessary to deliver power and data to this system. The second group is at Case Western Reserve University, led by Prof. D. Durand, and has been involved in recording and stimulation from peripheral nerves using cuff electrodes. Through this collaboration we intend to develop a fully integrated, low profile, multichannel, hermetic, wireless peripheral nerve stimulator that can be used with their nerve cuff electrode. This system can be directly used with other nerve cuffs that a number of other groups around the country have developed. Both of these collaborations should provide us with significant data on the reliability and biocompatibility of the package.

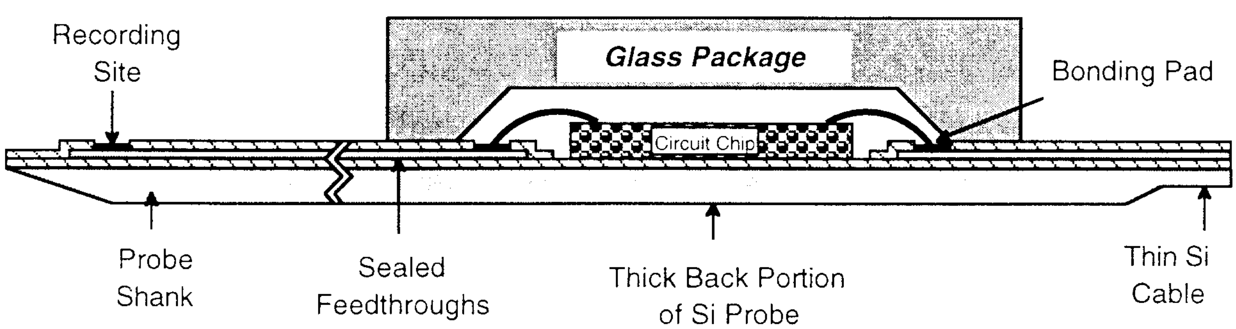


Figure 2: Proposed packaging approach for implantable neural prostheses that contain electronic circuitry, either monolithically fabricated in the probe substrate or hybrid attached to the silicon substrate containing microelectrodes.

II. ACTIVITIES DURING THE PAST QUARTER

2.1 Hermetic Packaging

Over the past few years we have developed a biocompatible hermetic package with high density multiple feedthroughs. This technology utilizes electrostatic bonding of a custom-made glass capsule to a silicon substrate to form a hermetically sealed cavity, as shown in Figure 3. Feedthrough lines are obtained by forming closely spaced polysilicon lines and planarizing them with LTO and PSG. The PSG is reflowed in steam at 1100°C for 2 hours to form a planarized surface. A passivation layer of oxide/nitride/oxide is then deposited on top to prevent direct exposure of PSG to moisture. A layer of fine-grain polysilicon (surface roughness 50Å rms) is deposited and doped to act as the bonding surface. Finally, a glass capsule is bonded to this top polysilicon layer by applying a voltage of 2000V between the two for 12 minutes at 320 to 350°C, a temperature compatible with most hybrid components. The glass capsule can be either custom molded from Corning code #7740 glass, or can be batch fabricated using ultrasonic micromachining of #7740 glass wafers.

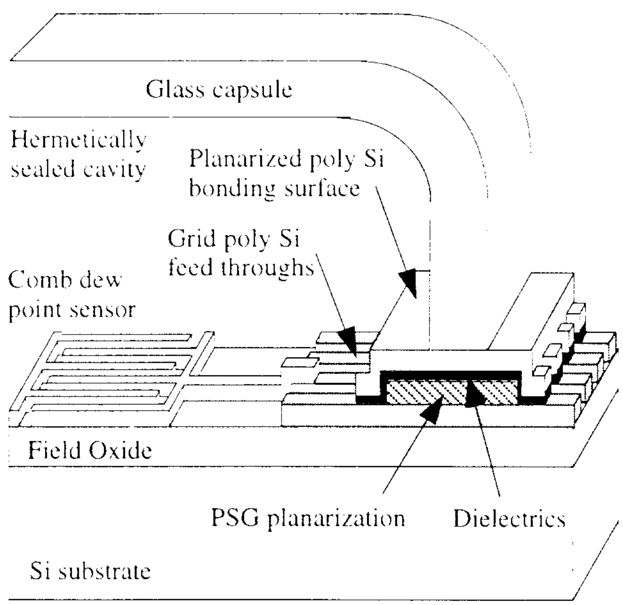


Figure 3: The structure of the hermetic package with grid feedthroughs.

During the past few years we have electrostatically bonded and soak tested over one hundred and sixty of these packages. The bonding yield is about 82% (yield is defined as the percentage of packages which last more than 24 hours in the solution they are soaked in). At the beginning of this quarter 4 devices were still being tested in saline at room temperature. These devices have been under test for over 5 years 10 months and show no sign of leakage. We should mention that these devices have been made with silicon substrates that are thinned (~150μm) and bonded to the custom molded glass capsules. We have also continued fabrication of silicon substrates and also continued several in-vivo and in-vitro tests using a wireless humidity sensor-hybrid coil system.

2.1.1 Ongoing Room Temperature Soak Tests in Saline

The packages soaked in phosphate buffered saline at room temperature have been under test for over 5 years and 10 months. These soak tests were started to complement the accelerated soak tests at the higher temperatures. Furthermore, upon close inspection of the top polysilicon layer, it is found that this top layer is there and is not etched after over 5 years and 10 months of testing. Our conclusion is that at room temperature we are below the activation energy required to cause dissolution of polysilicon and hence we have not yet observed any dissolution related failures. This observation is in accordance with the acceleration model used in interpreting the high temperature tests. Indeed, it seems to confirm that the activation energy for the dissolution of the substrate or the top polysilicon is high. Accordingly, due to the exponential decrease of the acceleration factor with temperature, the dissolution of silicon or polysilicon may not be significant at body temperature.

Out of the original 6 packages, one failed prematurely the first day and one failed because of mishandling. The other four devices are still under test and present no sign of leakage into the capsule after being soaked for 2139 days. Table 2 summarizes the data obtained from these soak tests.

Table 2: Data for room temperature soak tests in saline.

Number of packages in this study	6
Soaking solution	Saline
Failed within 24 hours (not included in MTTF)	1
Packages lost due to mishandling	1
Longest lasting packages in this study	2139 days
Packages still under tests with no measurable room temperature condensation inside	4
Average lifetime to date (MTTF) so far including losses due to mishandling	1736 days
Average lifetime to date (MTTF) so far excluding losses due to mishandling	2130 days

2.2 Wireless Monitoring of Humidity Inside Glass-Silicon Packages

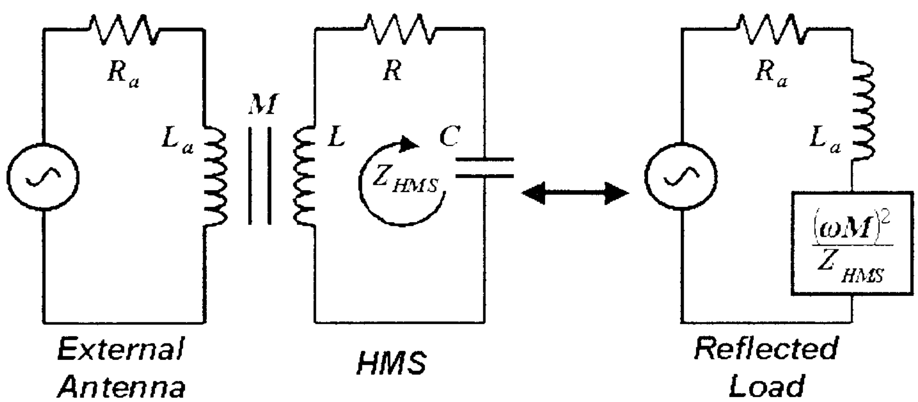
A wireless humidity monitoring system (HMS) has several benefits. First, it greatly facilitates the in-vitro testing of the packages, decreasing the detection threshold of moisture (as compared to dew point sensors used in the room temperature saline tests) and reducing mishandling and temperature cycling. In addition, it would allow one to automate the in-vitro testing procedure. Another benefit is that it allows continuous monitoring of humidity in packages that are implanted in animal hosts, thus providing important in-vivo hermeticity data.

In the previous quarterly reports, the wireless humidity monitoring approach was explained, which can be summarized as the following: a capacitive polyimide humidity sensor (HS) is wire bonded to an inductor made by copper wires wound around a ferrite core. This coil with the HS forms a LC tank circuit. The capacitive humidity sensor in this tank circuit responds to changes in humidity by changing its capacitance and thus the resonance frequency of the tank circuit shifts. When a coil (external antenna) is placed nearby this tank circuit: the maximum loading in the impedance measurements of the antenna is observed at the resonance frequency of the tank circuit allowing one to remotely monitor changes in humidity levels. We thus call the HS and the inductor combination the Humidity Monitoring System (HMS).

2.2.1 System Configuration

The wireless monitoring system consists of an external loop antenna (of inductance L_a), inductively coupled to the humidity monitoring system (HMS). The HMS is a hybrid copper wire coil (with inductance L and series resistance R) wire bonded to a humidity sensor (with capacitance C varying with humidity). The hybrid coil inside the package is modeled as a solenoid (a valid approximation, however, the actual coil has a rectangular shape) and for simplicity, we assume that the antenna coil and the HMS coil are coaxial.

The schematic of the system is given in Figure 4 and the equation nomenclature for this system is given in Table 3.



(a) System configuration (b) Equivalent circuit

Figure 4: The schematic of the humidity monitoring system.

Table 3: Equation nomenclature for the HMS.

Antenna:		Humidity Monitoring System:	
L_a	self-inductance (H)	L	coil self-inductance (H)
a	radius (m)	d	coil diameter (m)
N_a	number of turns	l	coil length (m)
μ_o	permeability (4πe-7 Ohms m)	S	cross sectional area (m^2)
		$\mu=\mu_o\mu_r$	magnetic permeability
Coupling:		μ_r	relative permeability of the core
M	mutual inductance	C	capacitance of the humidity sensor
Z	axis distance	R	series resistance

Figure 5 shows a HMS to be used to test the hermeticity of glass-Si anodic bonding. Figure 6 shows the antenna testing setup with a diced glass capsule revealing the HMS inside.

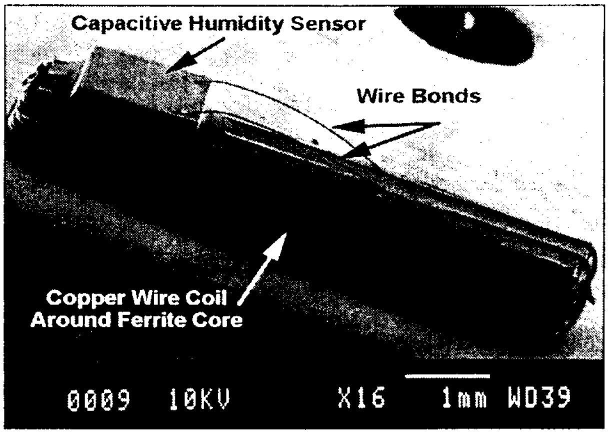


Figure 5: An assembled HMS.

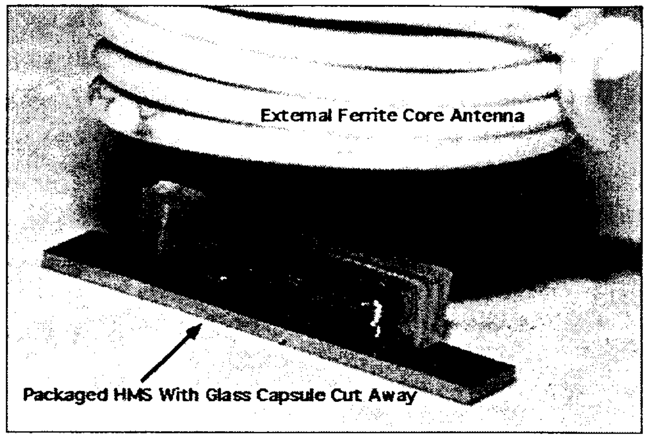


Figure 6: External Antenna and half-diced glass on silicon substrate with enclosed HMS.

2.2.2 High Temperature Soak Tests in Saline

An anodically sealed Humidity Monitoring System (HMS) has been soaking since April 1999 in phosphate buffered saline solution at high temperature. The package is inspected routinely under a microscope to detect any leakage path(s) on the phosphorous doped polysilicon bonding surface, and the resonant frequency of the HMS is measured to correlate this response with the humidity inside the sealed package. This data may provide useful information as to the failure and degradation processes of the package hermeticity. As of mid October 2000, neither a complete leakage path nor a corresponding HMS resonant frequency shift has been observed. Figure 7 shows the percent relative humidity change versus the number of days soaking at 97°C.

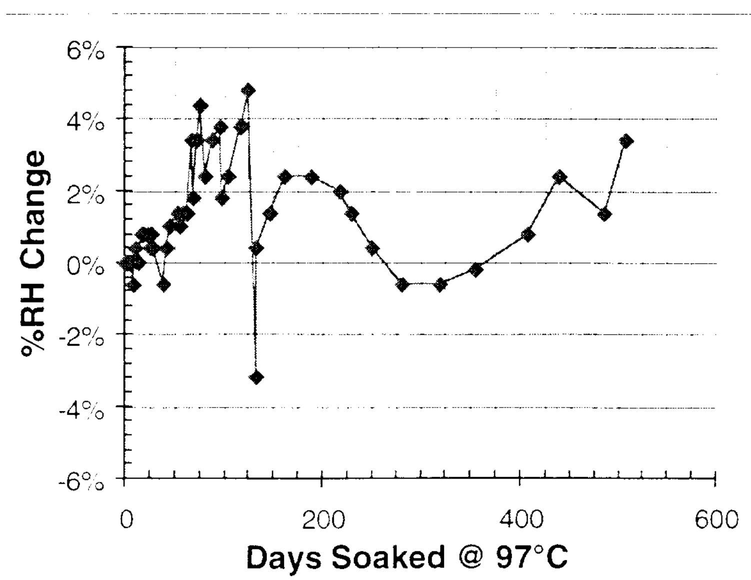


Figure 7: Telemetry data from a package soaked in high temperature saline soak test (97ΥC).

The frequency variations are attributed to day to day temperature fluctuations during testing. These variations are within experimental error and hence the HMS data and visual inspection analysis strongly suggest the anodically sealed package is hermetic for over 1.5 years.

An additional set of high temperature saline soak tests was initiated on July 25th. The test set consists of a total of 9 packages: 4 packages at 95°C, 3 packages at 93°C, and 2 packages at 85°C. The packages in this test set have phosphorous-doped polysilicon bonding surfaces and gold bond pads. Periodically the packages are visually inspected under the microscope to monitor any leakage paths/polysilicon corrosion. In addition, HMS's encapsulated within these packages are monitored manually or via the automated test station. To date 3 of the nine packages have failed – 1 at 85°C (package #16) and 2 at 93°C (packages #14 and #17). The wireless humidity monitoring results are summarized in Figure 8.

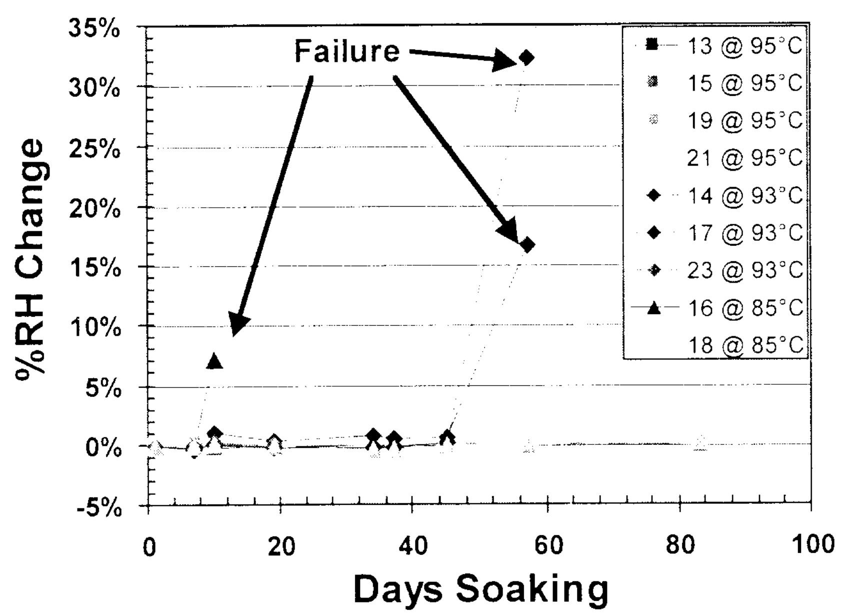


Figure 8: Wireless humidity monitoring data for high temperature saline soak tests.

The polysilicon corrosion is visually monitored for each of the packages. Some of these images are shown in Figures 9-11.

Packages 13, 19, 21, @ 95°C and 23 @ 93°C show little or no signs of etching. These high temperature saline soak test data, contrary to data from soak tests presented in the October 1999 quarterly report, shows a trend that phosphorous doped polysilicon etches slower for increasing temperature. The high temperature polysilicon corrosion data is not fully understood. However, the October 1999 quarterly also reports a saline etch rate vs. boron concentration in polysilicon. Therefore, it is hypothesized that variation phosphorous doping process may similarly affect the phosphorous doped polysilicon etch rate.

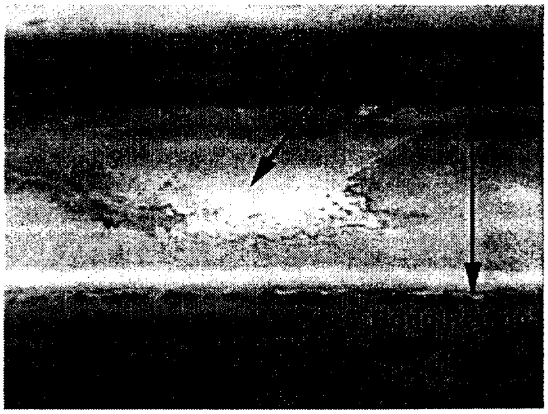


Figure 9a: Package #15, 95°C day 34

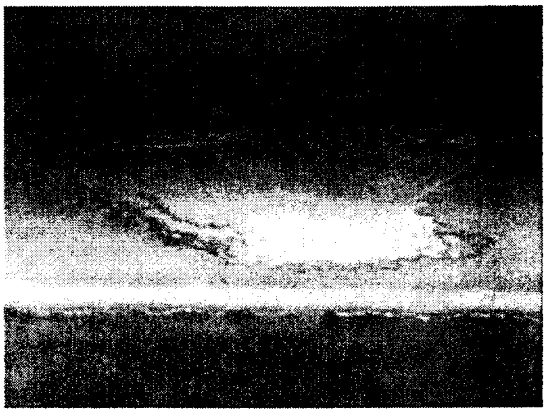


Figure 9b: Package #15, 95°C day 45

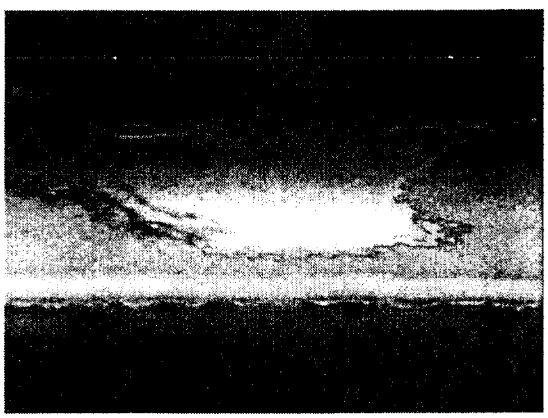


Figure 9c: Package #15, 95°C day 57

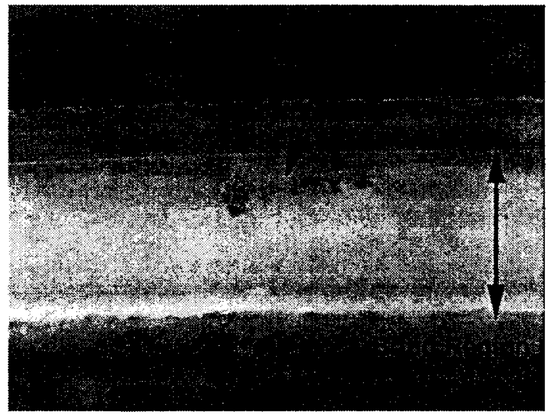


Figure 10a: Package #17, 93°C day 34

Figure 10a: Package #17, 93°C day 37

Figure 10a: Package #17, 93°C day 57

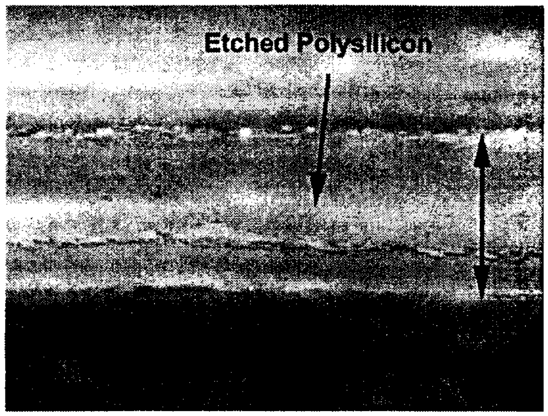


Figure 11a: Package #18, 85°C day 34

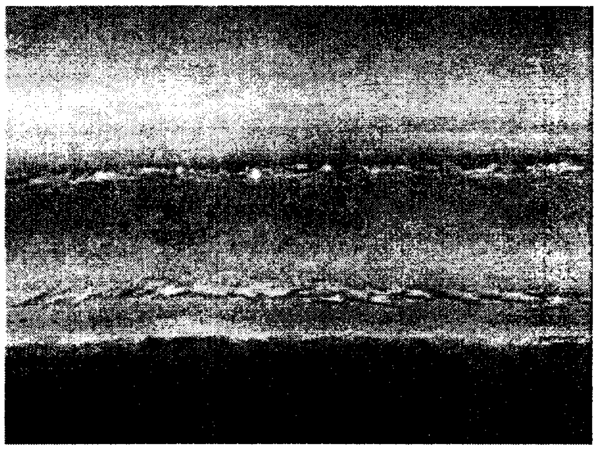


Figure 11a: Package #18, 85°C day 45

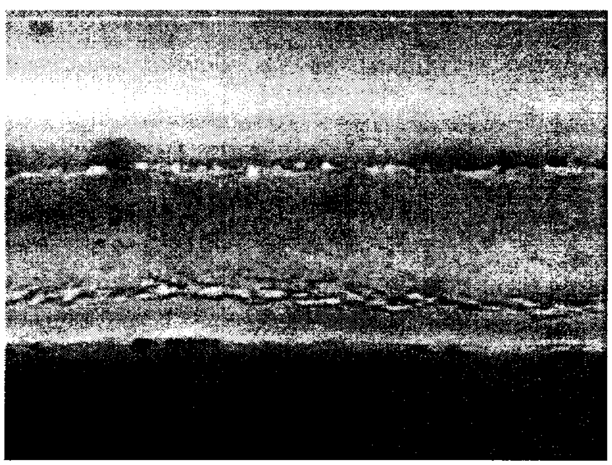


Figure 11c: Package #18, 85°C day 57

2.2.3 Automated In-Vitro Testing

The automated test station has been completed and a block diagram of the station is shown in Figure 12.

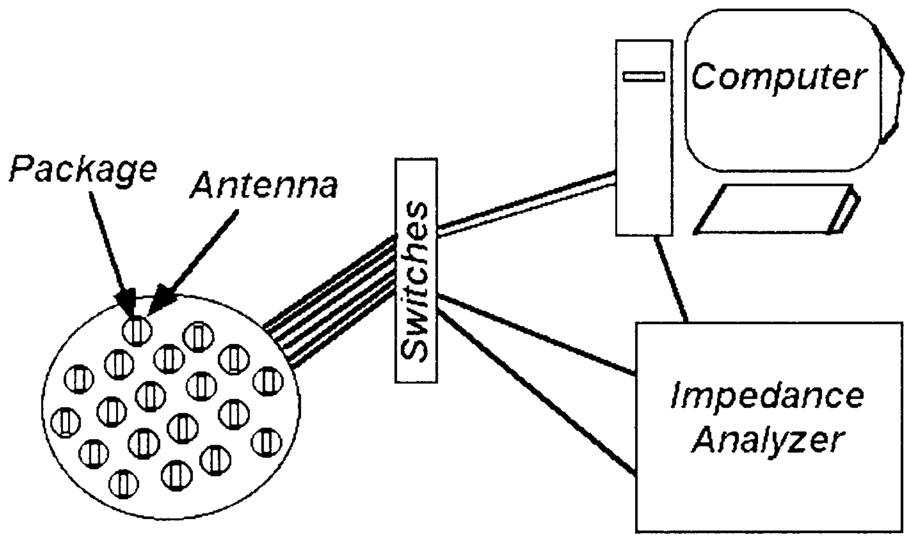


Figure 12: Block diagram of the automated test station.

As previously mentioned, ten hermetically sealed glass-silicon packages are placed in phosphate buffered saline solution and set in three ovens; 5 packages at 95°C, 3 packages at 93°C, and 2 packages at 85°C. The test station is operational, however a permanent configuration is under construction.

2.2.4 In-Vivo Testing

With the development of the wireless humidity monitoring system, it is possible to remotely monitor package integrity while the device is implanted in an animal host. Consequently, six devices were prepared and screened to insure hermetic seals. Each device passed a one-day room temperature soak in DI water to validate the seal prior to implant. The devices were then sent to the University of Michigan Medical School for implantation into guinea pig hosts. Two guinea pigs have been implanted with packages to monitor hermeticity in the in-vivo environment. Sites on the guinea pigs were selected to give the widest possible range of environmental conditions. On each host, one package was implanted into the leg, another into the abdomen, and a final one into the head for a total of three packages per host. Devices were implanted in the head beneath the skull but above the dura, under the skin but on top of the leg muscles, and in the abdominal cavity as depicted in Figure 13.

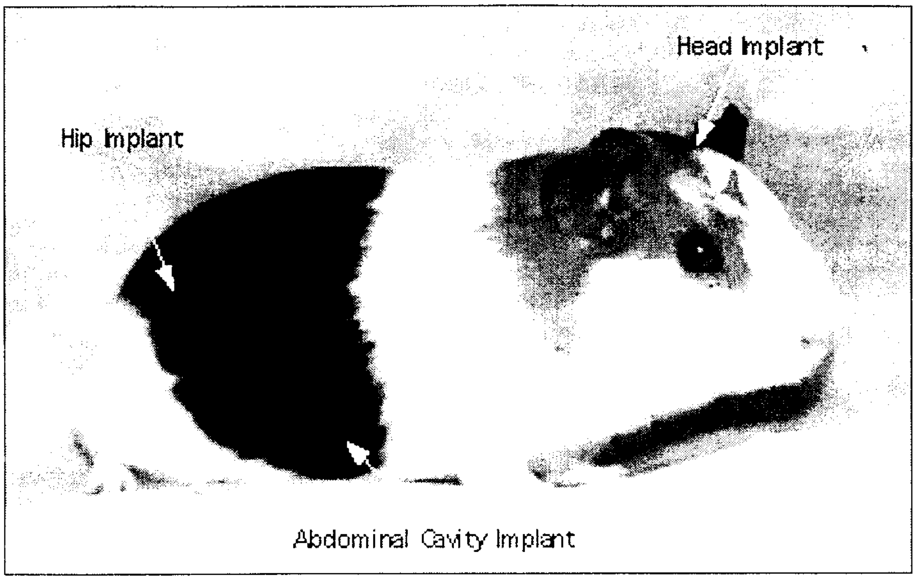


Figure 13: Locations of implanted packages in guinea pig host.

Tests were conducted immediately prior to and following implant, with no discernible change in system output. After this, devices were measured biweekly to detect shifts in resonant frequency resulting from changes of humidity in the package if any. As of October 2000 there has been no discernible shift in the output of any humidity sensing systems inside the packages. Given that a 50 kHz shift is considered significant, the output of the sensors, which varies by only a few kilohertz, indicates fairly steady humidity inside the packages. Figures 14 and 15 show the measured frequencies of the sensors over the duration of the test.

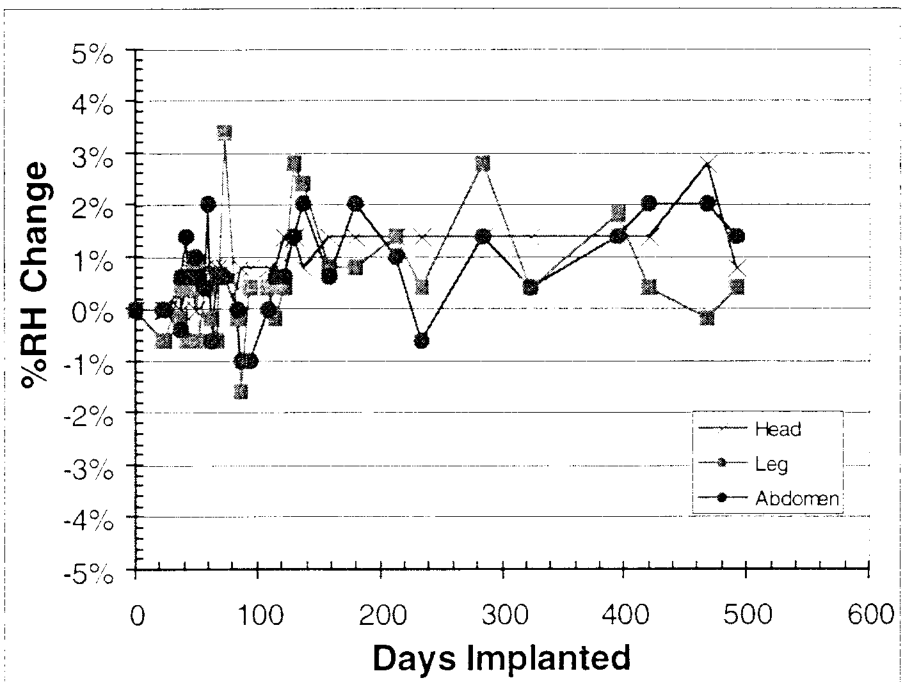


Figure 14: %RH change measurements over time for Guinea Pig A.

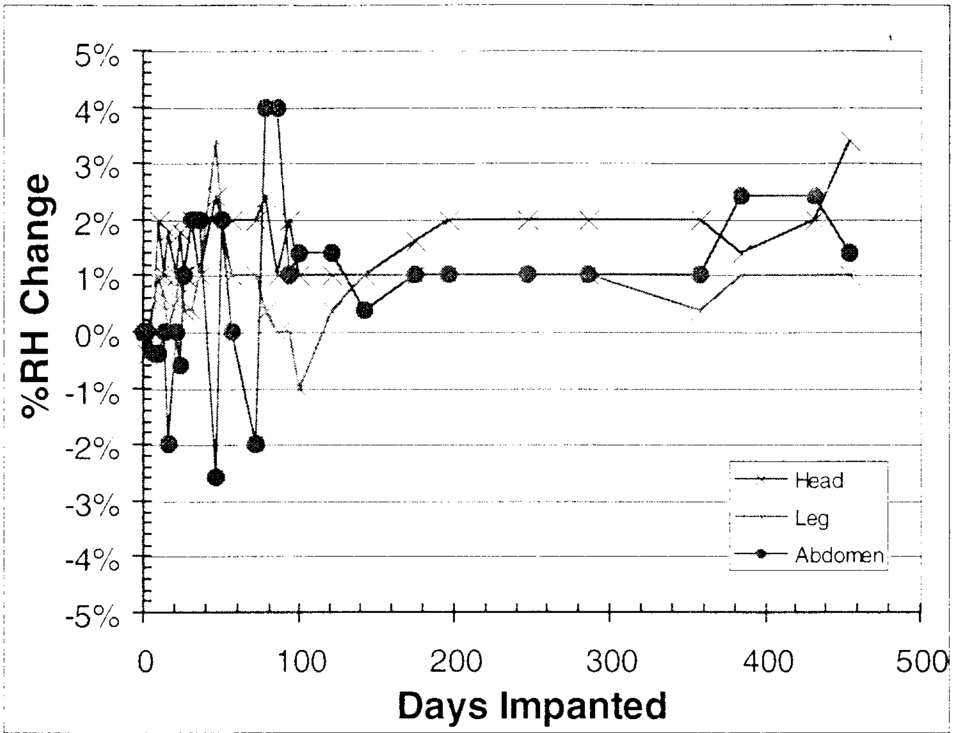


Figure 15: %RH change measurements over time for Guinea Pig B.

We will continue testing the packages in the guinea pigs biweekly and will report further data as it becomes available in the next quarter. The main goal from these tests is to demonstrate that these packages can stay hermetic inside animal hosts.

2.3 A Passive Wireless Integrated Humidity Sensor

A passive wireless integrated humidity sensor (IHS) is being developed to address the deficiencies of the HMS discussed in the September 1999 NIH report and summarized in Table 4.

Table 4: Deficiencies of the hybrid HMS design

– Tedious time consuming fabrication
– Multiple component system – low yield
– Variation of performance due to hand assembly
– Large device size

The design is shown in Figure 16 and is applicable to the same wireless testing model described in section 2.2.1.

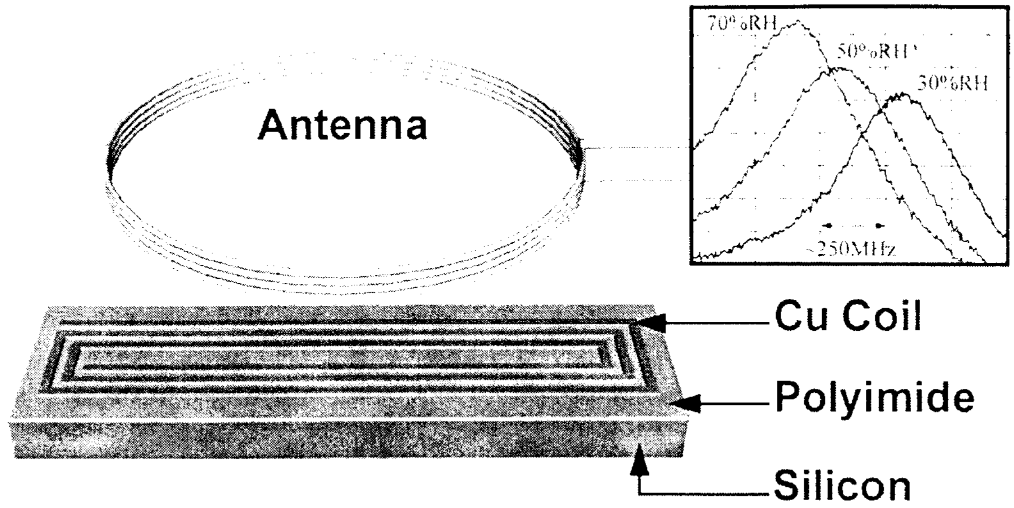


Figure 16: A passive wireless integrated humidity sensor design.

The equivalent circuit of this design is an LC tank circuit as shown in Figure 4 where the inductor, with inductance L and series resistance R, is the planar copper coil and the capacitor, with capacitance C, is between the copper coil and the conductive silicon substrate separated by humidity sensitive polyimide as shown in Figure 17.

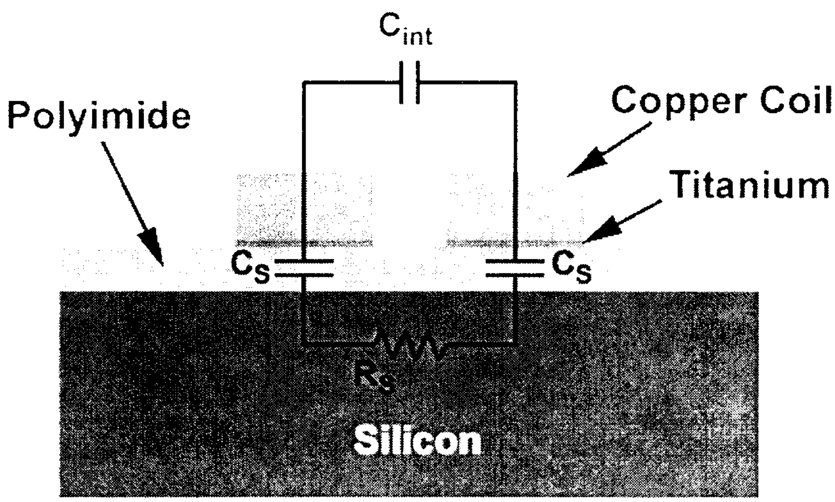


Figure 17: Circuit elements of the IHS

New devices have been fabricated to support the development of the IHS model however test results have not yet been completed.

The focus of the new devices and test structures is to determine the source of and theoretically quantify the IHS capacitance. In order to determine this capacitance the dielectric polyimide thickness must be known. The polyimide thickness vs. spin speed results of the newly fabricated devices are shown in Figure 18.

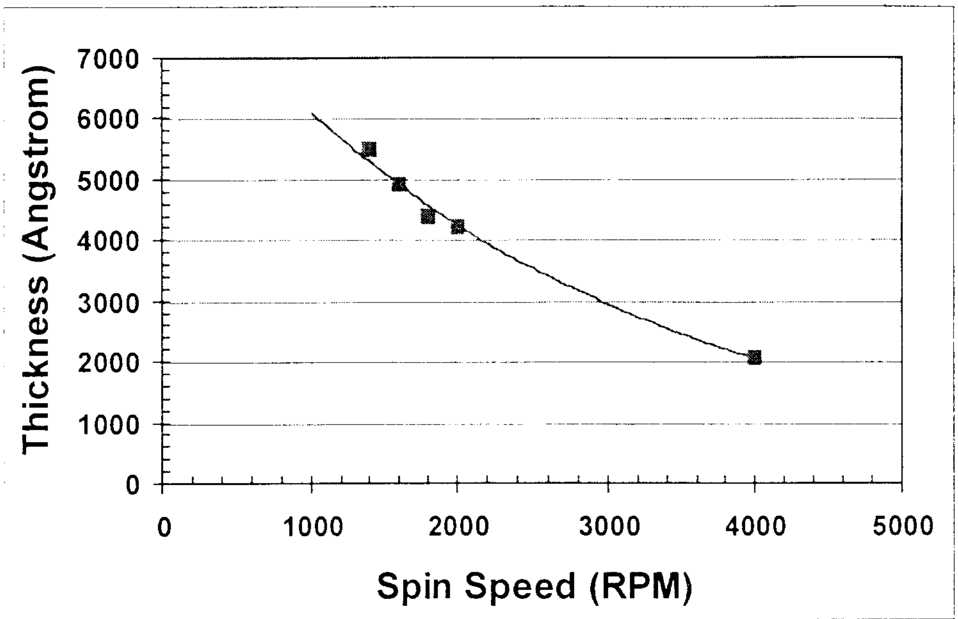


Figure 18: PI-2613 thickness vs. spin speed (after curing).

An abstract entitled "A Passive Wireless Integrated Humidity Sensor" describing the FI-HMS and wireless telemetry monitoring was accepted for presentation at the MEMS 2001 conference.

2.4 Novel Packaging Technologies

In the interest of developing a Si-Si bonding technology for flip chip devices, several novel encapsulation techniques have been investigated. The goal of this research is to find a technology that is biocompatible and can be used to make complicated bioMEMS systems. Current microsystems designed for biological applications are limited by low yield resulting from complicated process flows. By developing a technology that can separate the complexities of circuit design from the complexities of building implantable microsystems, it is possible to greatly simplify the production of implantable biosystems. Critical to this research is to develop a method that makes low temperature hermetic biocompatible encapsulation possible for Si-Si bonding. The long-term goal of this research is to enable the production of devices that are structurally similar to Figure 19.

2.4.1. Packaging experiments for the neural Probes

As part of our work on hermetic biocompatible packaging, we proposed to extend our technology to devices other than the microstimulator. One obvious potential application of this technology lies in the development of a packaging technology for active neural probes. The active neural probe is designed to record neural signals at multiple sites, but has been heretofore limited to acute implants because there was no adequate package to protect the circuitry for long term implants. As a result, we are adapting our packaging technology to develop a hermetically sealed neural probe for chronic implantation. The most recent research into neural probes has focused upon using electroplated films to seal the probe. A relatively thick film of gold should provide a long-term hermetic seal for the probes. Figure 20 shows the concept of the packaged neural probe.

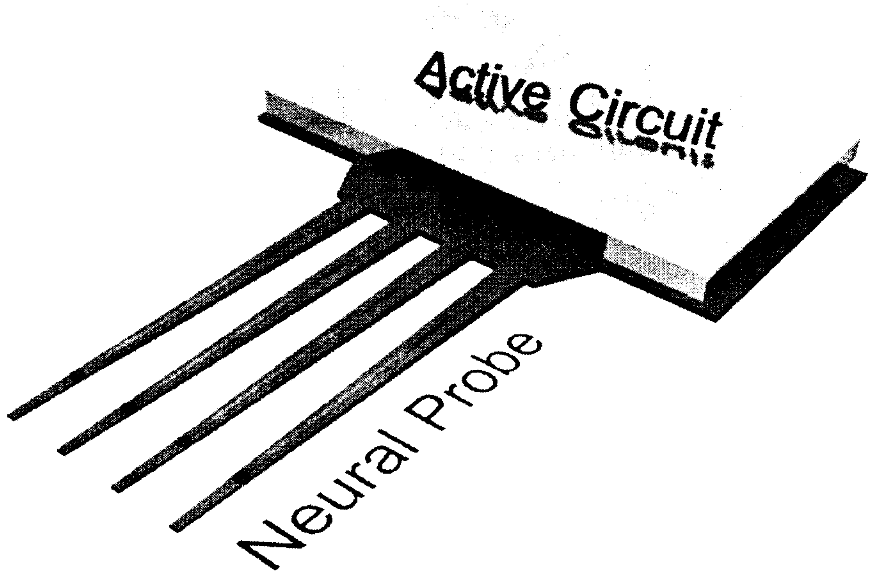


Figure 19: Schematic of our long-term plans for flip chip technology

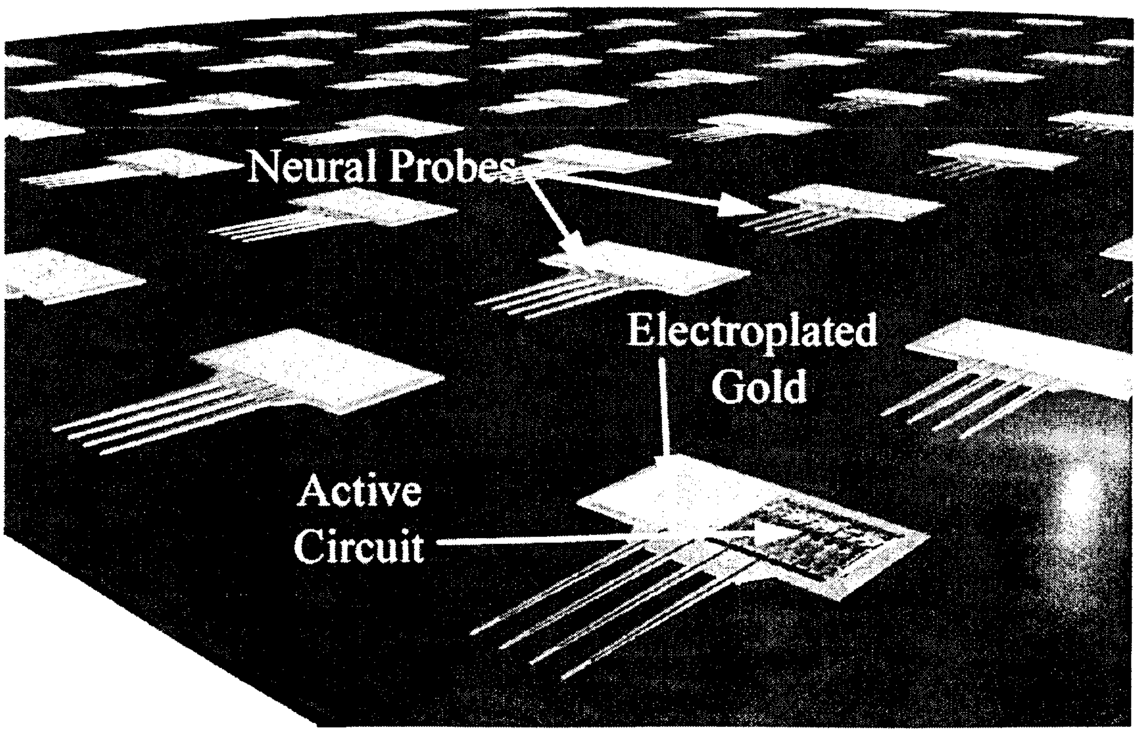
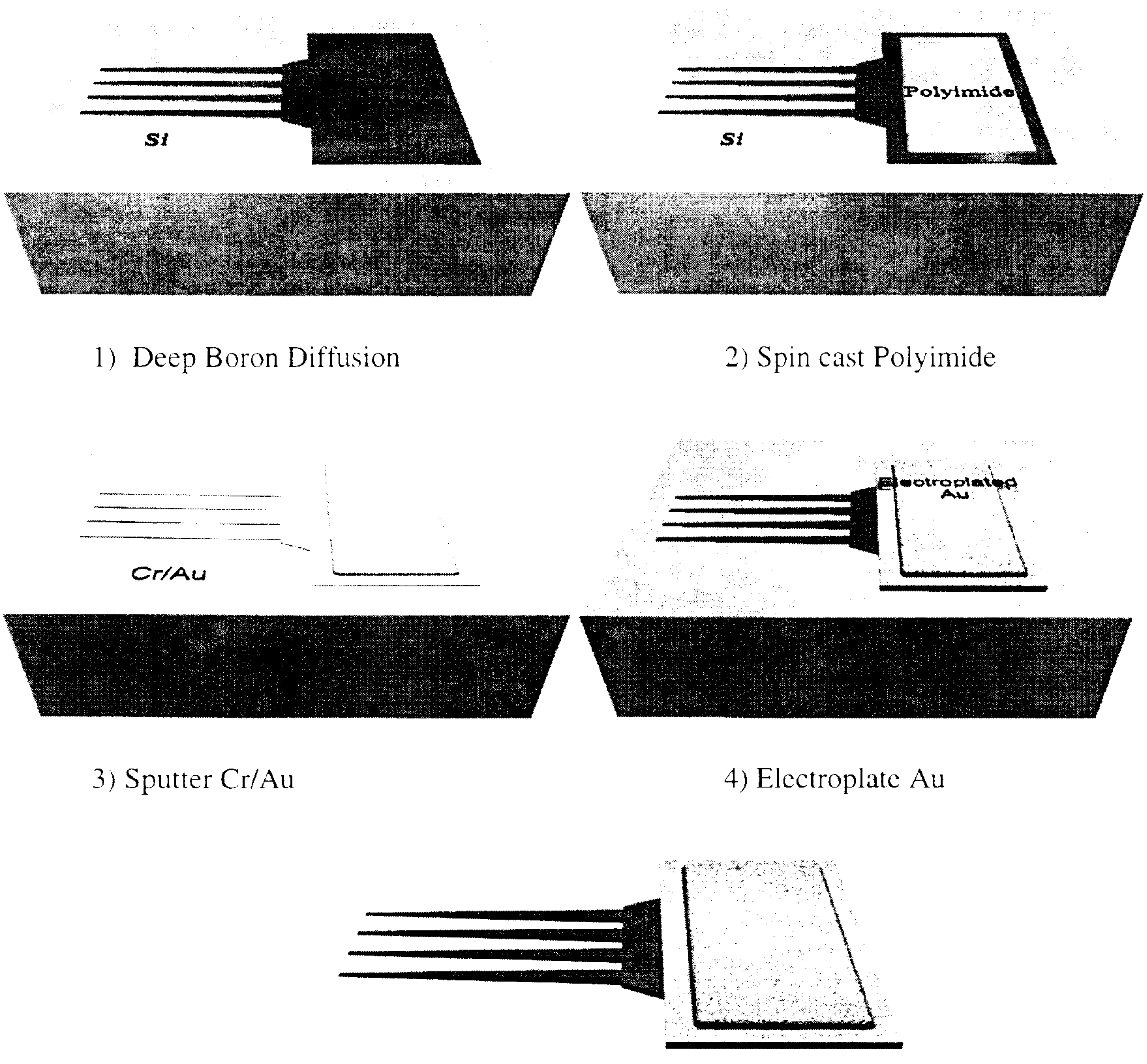


Figure 20: Schematic of packaged Neural Probe

The initial step in constructing the packaged neural probe is to build a test structure to study the feasibility of wafer level encapsulation. While the technology for building the neural probes is well established, a method for wafer level encapsulation is not. Instead of using expensive active probes to prove the initial efficacy of this encapsulation method, structures utilizing encapsulated polyimide were developed. The process for this test structure is shown in Figure 21.



1) Deep Boron Diffusion

2) Spin cast Polyimide

3) Sputter Cr/Au

4) Electroplate Au

5) EDP release

Figure 21: Fabrication process for neural probe test structure.

In the EDP release, a hermetically sealed package will protect the underlying polyimide. However, if there is a defect in the seal, the polyimide will dissolve. As a result, a simple cross section of the device after release reveals if there is a hermetic seal. In the past quarter, these test structures were fabricated.

The probes were cross sectioned by removing the silicon from the back of the probes and examined for polyimide. Figure 22 shows an example of probe cross sectioning.

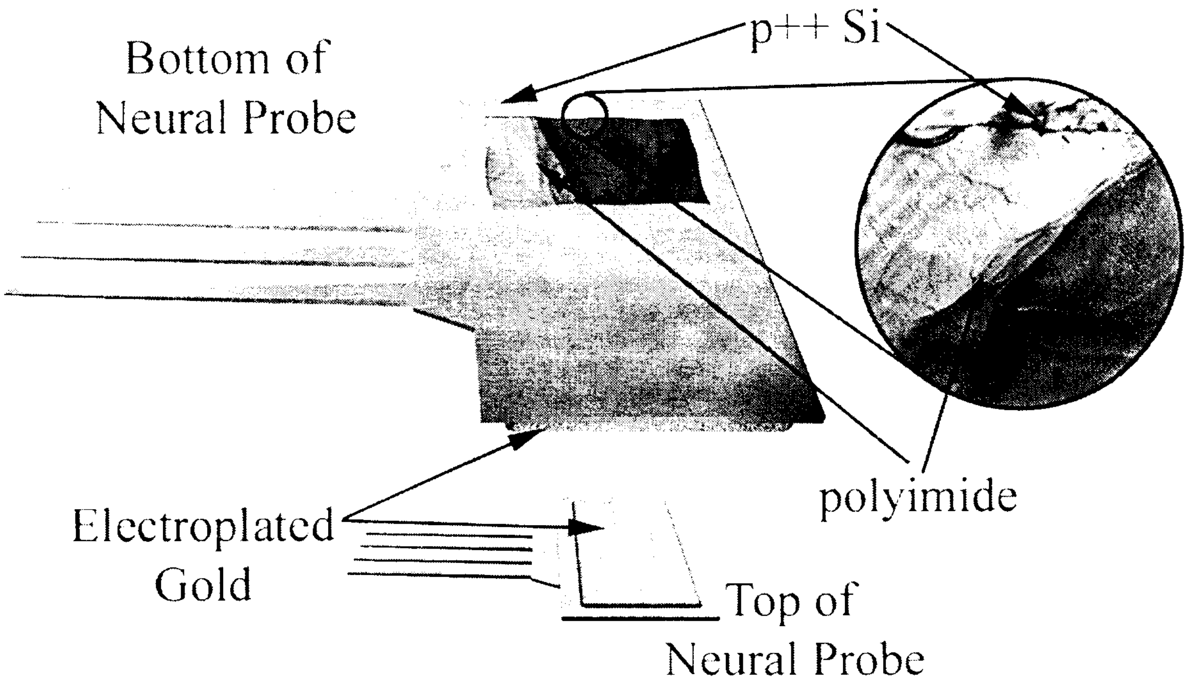


Figure 22: Diagram of cross sectioned probe.

Figure 23 shows a failed probe, it shows the chrome adhesion layer on the probe and the gold electroplated foil. This device failed due to lithographic defects.

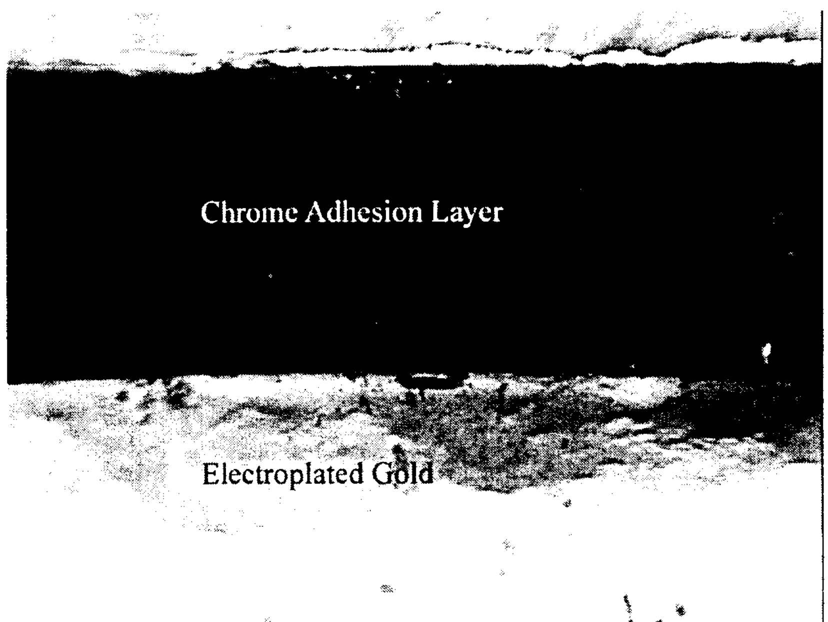


Figure 23: Failed probe packaging viewed after cross section.

After adjusting the parameters of the process, the yield was improved and the devices survived the packaging process. Figure 24 shows cross sections of surviving probes. The polyimide, which contains trapped bubbles, is clearly visible and looks remarkably distinct from the gold foil.

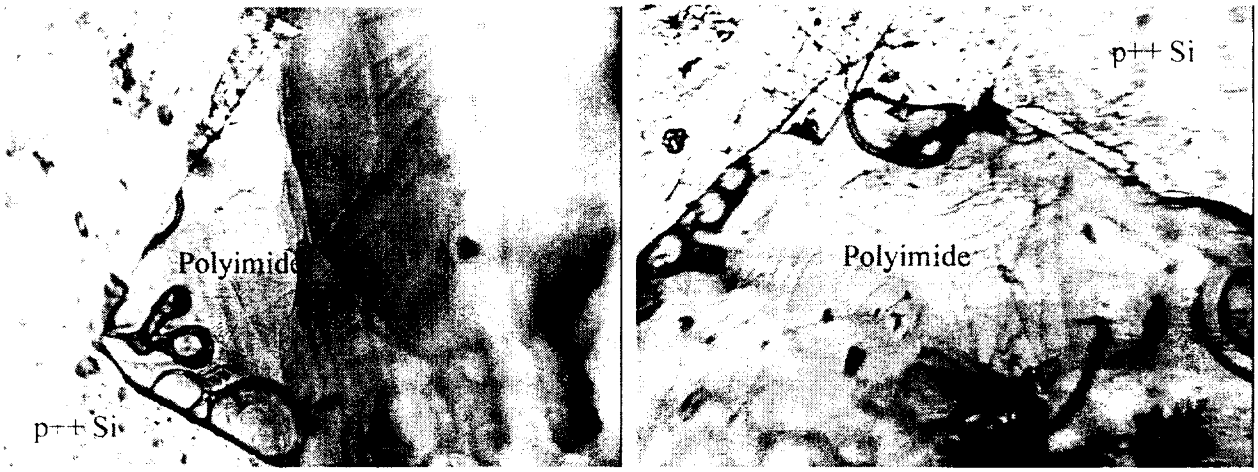


Figure 24(a, b): Cross section of surviving probes. The polyimide is clearly visible next to the remains of the boron-doped silicon.

This shows that electroplated films are capable of encapsulating devices for long-term implants. Given that these devices have already survived a 10 hour EDP release, there is a high probability that they will have a long lifetime inside the body. Figure 25 shows an SEM of the packaged probes.

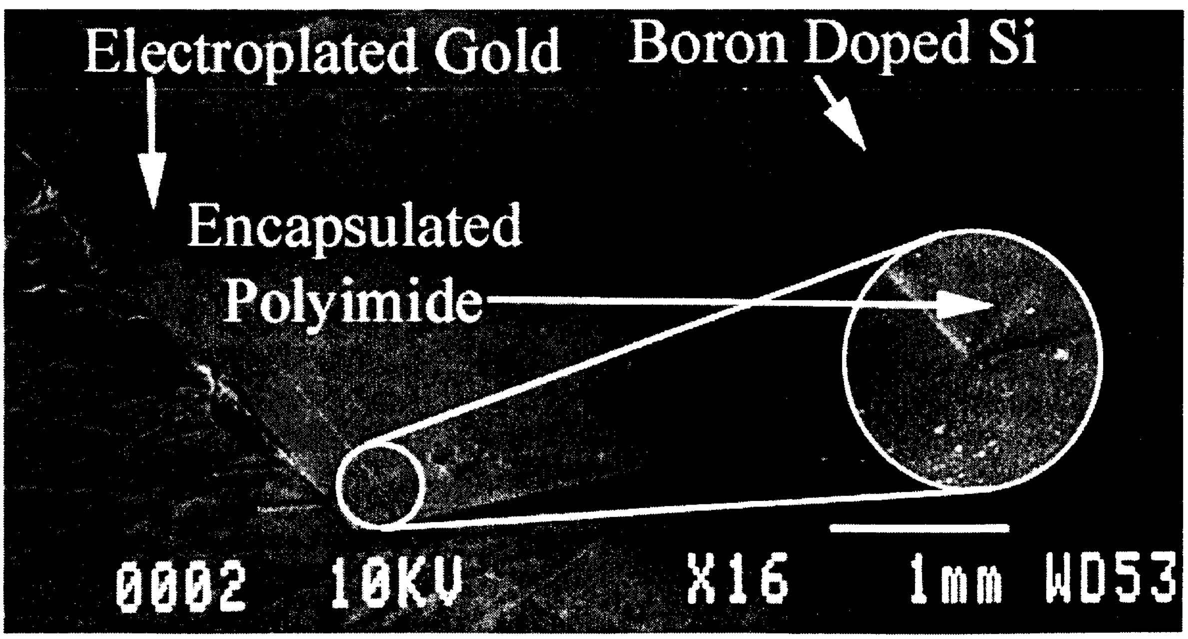


Figure 25: SEM of the packaged probe.

Using this technique, we have been able to demonstrate a high yield packaging technology at the wafer level. After a one hour EDP soak, we have demonstrated a yield of 88%, with defects showing an orientation dependence. For probes on the outside of the wafer, where the film was non-uniform, the yield was low, while probes in the center of the wafer had a nearly 100% yield.

In order to obtain long-term measurement data, a test structure has been designed that will enable the generation of more accurate lifetime data. This test structure is depicted in Figure 26.

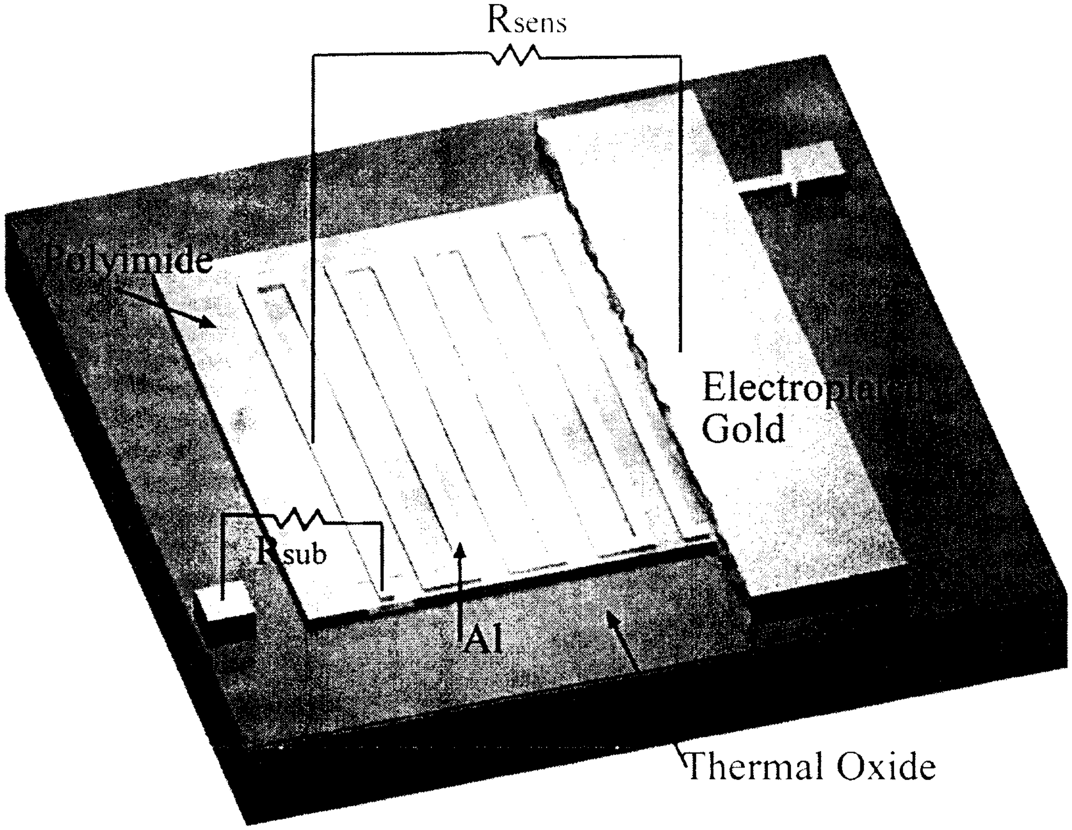


Figure 26: Test structure for long term low profile soak tests.

This test structure utilizes an aluminum resistor that runs the length of the package. The resistor will corrode in the presence of saline, thus changing resistance. By using this structure with our automated test station, we plan to generate significant lifetime data on our low profile packages.

2.4.2 Solder for interconnections

As part of our plans to develop biocompatible flip chip technology for implantable probes and stimulators, we have begun to investigate the use of solders for electrical and mechanical connectors between the circuit and sensor wafers. A schematic of the flip chip is shown in Figure 27.

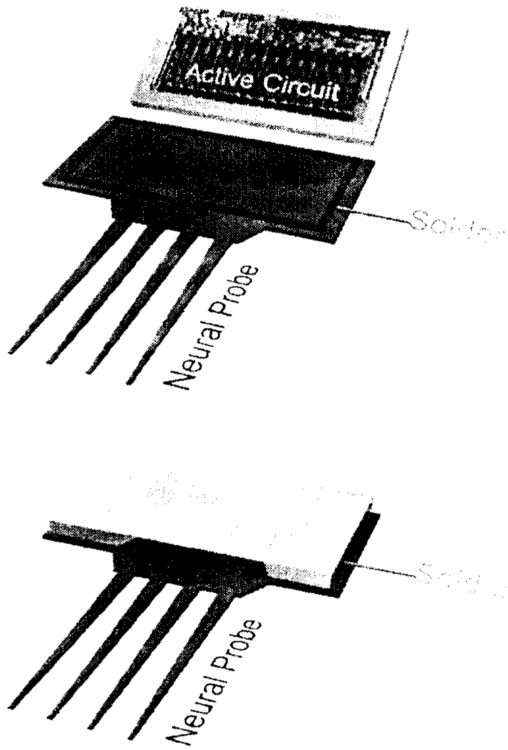


Figure 27: Concept of solder based flip chip

Eventually this technique will be used to demonstrate wafer level flip chip packaging, as shown in Figure 28.

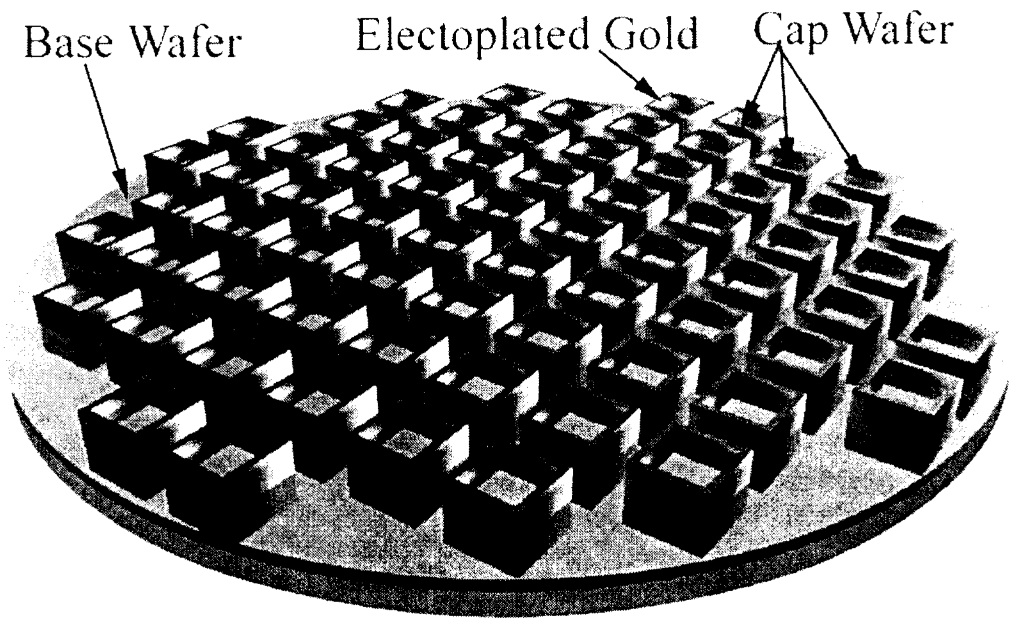


Figure 28: Schematic of finished flip chip wafer.

The use of solder has been well established in the electronics industry for years. Our research into this area is only to develop a technology for use in future biocompatible flip chips, not to make substantial improvements into soldering technologies.

In the previous quarter we demonstrated the use of solder for electrical and mechanical connection. In this quarter we worked on adapting this process to a wafer level flip chip. Development in this area is ongoing and has not yielded a finished device.

2.5 FINESS chip

The FINESS chip receives its power and data from a 4MHz carrier signal with pulse modulation. The optimum pulse duration is 40 µseconds. The pulse encodes the data bit, as shown in the figure below.

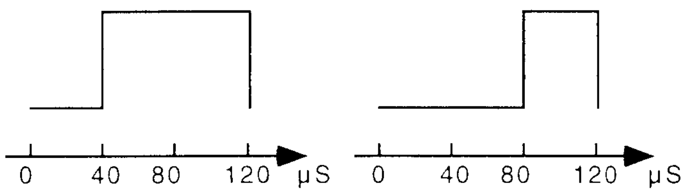


Figure 29: Bit encoding with nominal width pulses.

The modulation waveform encodes several parameters that are required for the FINESS chip to operate. The parameters are illustrated in the table below.

Table 4: Required parameters for stimulation.

Parameter	Range	Required Bits
Address of Device	Selection from up to 8 devices	3 bits
1st Phase Current Magnitude	0 to 2 mA (32 steps of 64.5 µA)	5 bits
2nd Phase Current Magnitude	0 to 2 mA (32 steps of 64.5 µA)	5 bits
Electrode Selection	Selection from 8 electrode pairs	3 bits
1st Phase Duration	4 to 2050 µs (1024 steps of 2 µs)	10 bits
Inter-phase Delay	12 to 1932 µs (16 steps of 128 µs)	4 bits
2nd Phase Duration	4 to 2050 µs (1024 steps of 2 µs)	10 bits
Parity Bits		5 bits
Total		*45 bits*

The nominal time required for each stimulation is shown below.

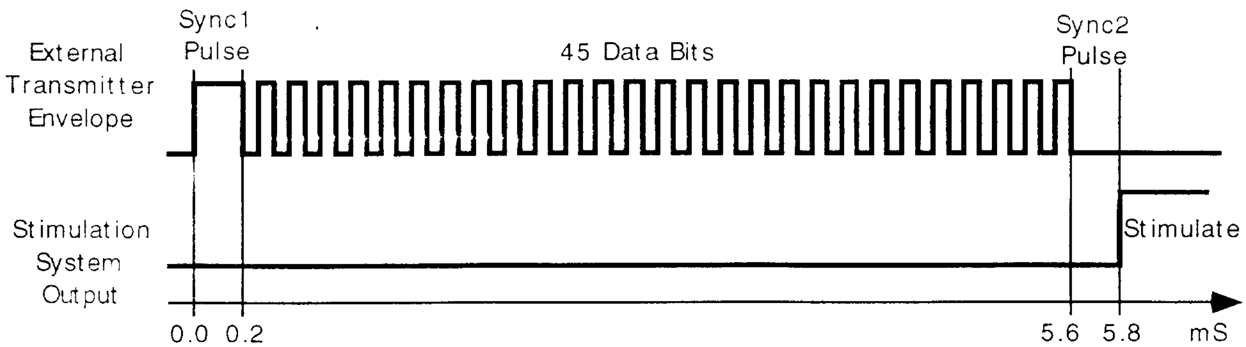


Figure 30: The nominal time for each stimulation command.

The FINESS chips were tested with these parameters. Since FINESS does not have handshaking capability, all parameters have to be adjusted carefully before testing the dice. To that end, the ability of the input modulated waveform to power the chip, and for the envelope detector to detect the input modulations was tested. This was followed by testing the digital circuitry as a separate block. For the digital circuitry, the inputs were the clock, the Power-on-reset, the digital modulating voltage and the power supplies.

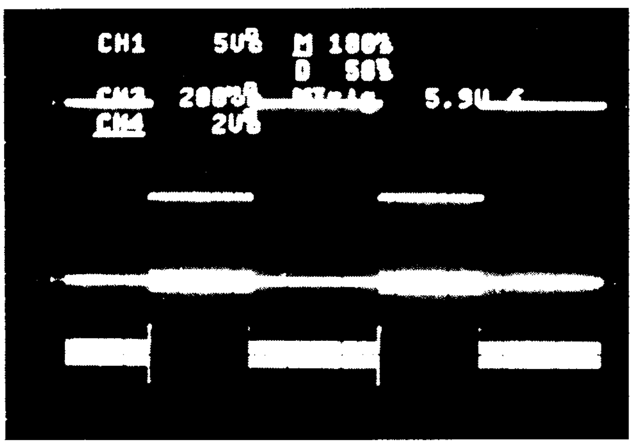


Figure 31: The envelope detector output to the input modulating voltage.

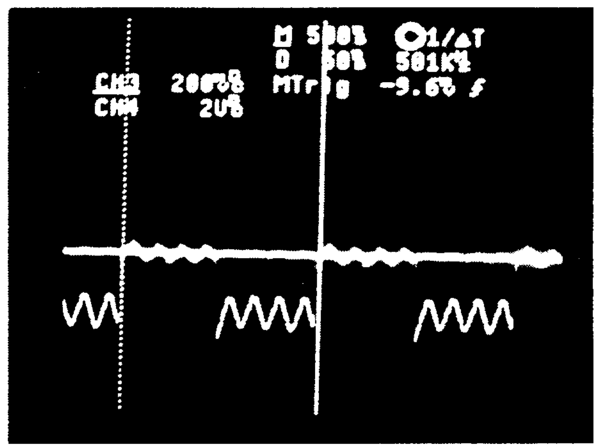


Figure 32: The clock generator output.

Figure 31 show the functionality of the FINESS chip. The analog front-end, which consists of the voltage regulator, the clock generator, envelope detector and the power-on-reset, is shown to be functional. The digital control circuitry is also shown to be working, with the stimulus output signal shown in Fig. 32 in response to the given modulation signal. The next step in testing is to combine both of these blocks with the output current source block to see the functionality of the whole chip.

III. PLANS FOR THE COMING QUARTER

Further research into thick resist materials and process for increased plating height will continue. IHS devices will be characterized and an accurate model will be developed so that the design can be optimized for sensitivity, testing distance. After testing and characterization of the IHS devices they may be used for humidity monitoring in the glass silicon package. We will continue wireless monitoring the of the implanted and accelerated test packages.

A batch-fabricated low profile package will be developed for accelerated testing purposes. The batch-fabricated packages will greatly reduce the throughput time for obtaining hermetically sealed packages for accelerated testing.

In the coming quarter we plan to finish our lifetime test structures and to measure the reliability of our electroplated gold packages. We also plan to continue our research into solder bonding in order to demonstrate a biocompatible flip chip.

In the coming quarter, we plan to continue testing the complete FINESS chips using a telemetry link and will begin work on assembling the chip together with a peripheral cuff electrode for peripheral nerve stimulation applications.